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Schottky diodes make IC scene

With reproducibility problems licked, these devices make attractive elements; they permit unusual component combinations, save chip real estate, reduce power dissipation, and enhance production yields

By R.N. Noyce, R.E. Bohn, and H.T. Chua

Intel Corp., Mountain View, California

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Solid state

Schottky diodes make IC scene

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Schottky diodes, because they don't store charge, open new worlds to digital integrated circuits. Diode-transistor logic with Schottky diodes can be made as fast as transistor-transistor logic and emitter-coupled logic. What's more these devices reduce an IC's power dissipation and permit unusual combinations of components on a chip. They also make large-scale integration easier to achieve because more functions can be performed in less area. Not the least of their virtues is the fact that they can increase production yields.

For all these advantages, Schottky-diode IC's have not been commercially available. Intel Corp., however, has concentrated on their development and is now making Schottky diodes that are stable and reproducible. The company has committed Schottky IC's to commercial production, and has found that they live up to expectations. Their first Schottky IC will be introduced in the next few weeks.

Structurally, the Schottky diode is little more than a metal in contact with a semiconductor. As long as aluminum is used for the metal, formation of Schottky diodes in a monolithic IC is compatible with standard processing. Some provision is needed to prevent high-field effects at the edge of the metal contact, but this too is compatible with standard processing. In fact, once reproducibility problems have been solved, Schottky diodes actually simplify processing of high-speed digital IC's because gold doping is eliminated.

The Schottky diode has been around in one form or another for a long time—the crystal detector in early radios, for instance. The modern device, which gets its name from the German scientist who developed the first valid theory of metal-semiconductor rectification, can be used to enhance the performance of existing IC designs as well as to develop entirely new configurations with exceptional features.

In the forward-biased p-n junction, current is carried by holes flowing from the p-type material into the n-type material, and electrons flowing from the n to p material. Either case results in an excess of minority carriers near the junction. If the voltage is reversed these carriers will flow back across the junction, creating a high current until the supply is exhausted. In other words, the p-n junction can't be turned off immediately.

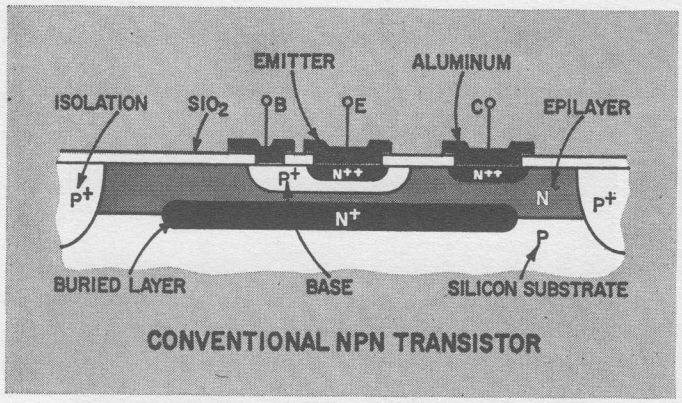
In a Schottky diode made of aluminum on n-type silicon, essentially all of the forward current is carried by electrons flowing from the semiconductor into the metal. They quickly come into equilibrium with the other electrons in the metal, so there is effectively no stored charge to prevent rapid switching. Another major point of difference between the Schottky and the p-n junction diode is that the former has lower forward voltage for a given current.

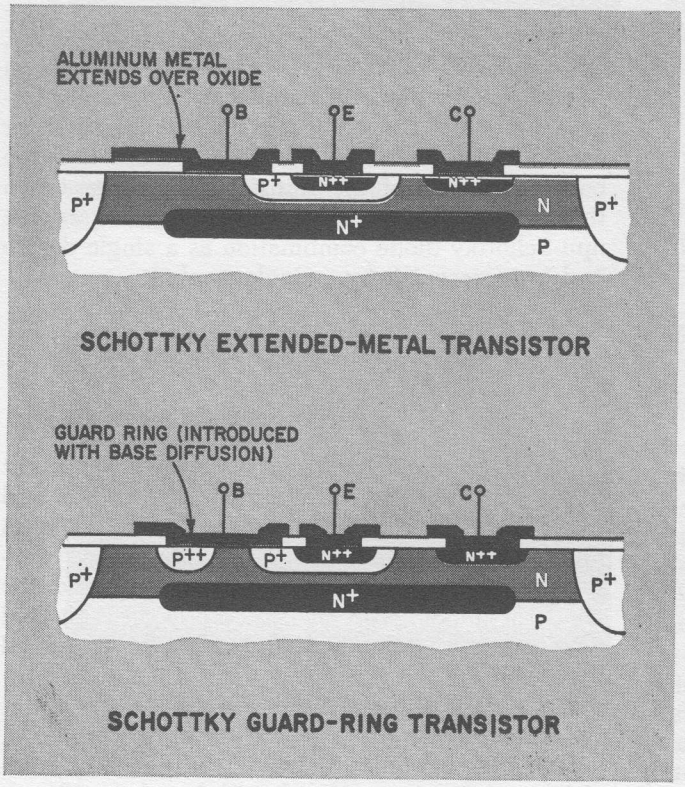
In a practical circuit the Schottky diode is placed in parallel with the base-collector junction of an npn transistor; the metal electrode is connected to the base and to the n region of the collector, where it forms a rectifying contact.

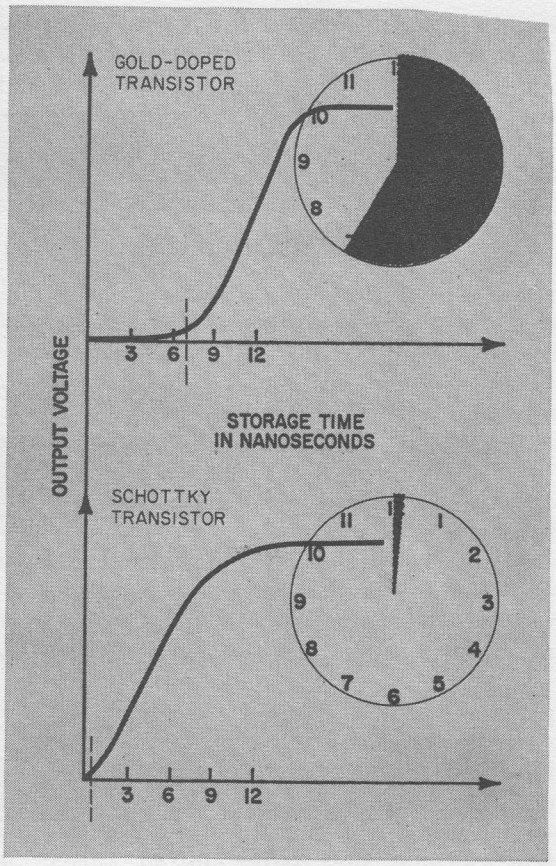
Since the Schottky diode has a lower forward voltage compared with the collector-base junction, the diode clamps the transistor and diverts most of the excess base current through the Schottky diode, preventing the transistor from saturating. There's no charge storage, either in the transistor or diode.

Clamping techniques have been used in the past to prevent charge storage. Most are variations of the Baker clamp proposed in 1956.[1] In this scheme, a germanium diode shunts the collector-base junction of a silicon transistor to prevent it from being forward-biased; some charge is still stored in the germanium diode. The Schottky IC employs clamping but charge storage is eliminated.

In the past, other efforts to improve switching







Double duty. In a Schottky transistor a Schottky diode is in parallel with the collector-base junction. The base metal is also the anode of the diode; the collector diffusion is also the diode cathode. Edge effects can be avoided with the extended-metal or guard-ring structure. The curves compare storage time of the gold-doped and Schottky transistors. The former uses up 7 nsec of recombination time before it can change state; the Schottky transistor responds almost instantaneously.

speed by reducing or avoiding stored charge have taken two approaches: process innovation and novel circuit design.[2, 3, 4]

Attempts to minimize storage time through novel circuit designs have had varying success. The most familiar is current-mode switching, which avoids saturation (and hence charge storage) by controlling the collector current so that the collector-base junction never goes into forward conduction. Current-mode logic is fast—propagation time through a gate can be as low as 1 nanosecond—but when such IC's are assembled in a system, they will oscillate unless precautions are taken to control their input impedance characteristic.

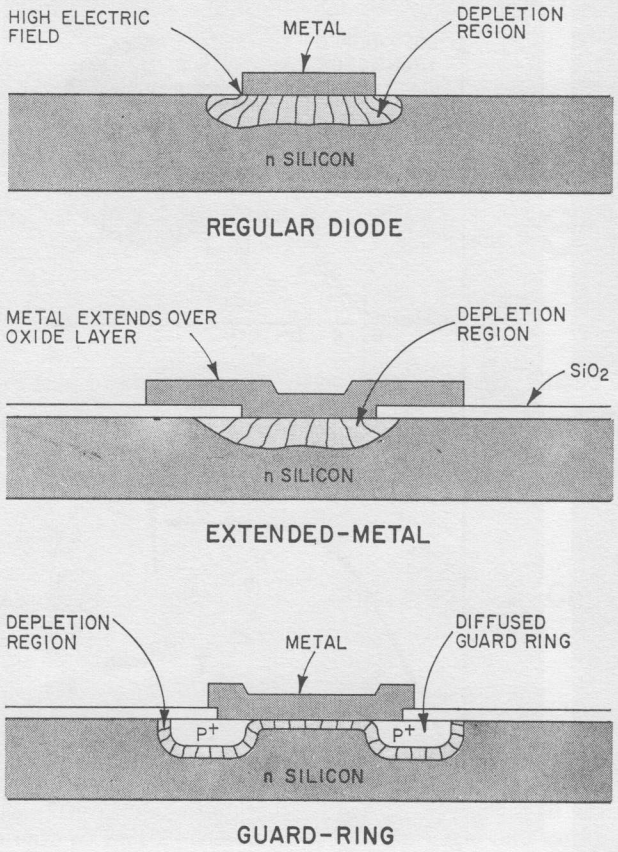
Off the gold standard

The standard processing approach to charge-storage reduction in conventional IC's is gold doping. Since gold acts as a recombination center, it reduces the lifetime of minority carriers; that is, it shortens the time for recombination of holes and electrons. Intentional reduction of minority carrier lifetime is somewhat ironic. In the early days of transistors, much effort was expended in increasing the minority carrier lifetime to increase current gain and decrease junction leakage.

Unfortunately, the gold diffusion has some highly undesirable side effects. It tends to reduce gain (h_{FE}). If this value gets too low, the IC's won't function because the transistors either don't saturate or have excessive turn-on delay. The manufacturer can use a narrower base to get higher h_{FE}, but this can lead to excessive junction leakage.

The Schottky process sidesteps this problem. Without the need for gold doping, low storage time and high h_{FE} can be achieved simultaneously.

Another difficulty with gold doping is the lack of selectivity—if one transistor must be high speed, all the others on the chip have to be high speed too. But with the Schottky process, fast and slow devices can be mixed on the same chip. This freedom of choice in component characteristics is exploited



Edge effect. The high field concentration at the edge of the regular Schottky structure can cause spurious currents. These can be avoided by means of the extended-metal structure or the guard ring.

in some of Intel's new products.

But before Schottky diodes could be successfully integrated manufacturers had to resolve some dilemmas; diode characteristics were often grossly different from theoretical predictions and devices were not reproducible. The cause, it has since been found, is the high electric-field concentration at the periphery of the metal electrode, as shown above. This field, through the mechanism of tunneling, can lead to spurious currents that dominate the ideal diode characteristic. Because the shape of the edge varies from one device to another, the magnitude of these excess currents can vary greatly.

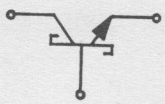
Two solutions to this problem were recently proposed.[5, 6, 7] In one, the metal electrode extends over the silicon-dioxide passivating layer. With this dielectric layer between the metal and the semiconductor, the electric field at the periphery of the electrode is greatly reduced, and the diode has ideal characteristics.

In the other solution, the edge of the metal extends over a diffused p^+ guard ring. This also reduces the field, and moves it away from the edge of the electrode so that it can't affect the diode. Again, the characteristics are ideal.

Electrically, the aluminum-silicon Schottky diode differs somewhat from the diffused p-n junction diode in its d-c forward current-voltage characteristic, shown at right. The forward voltage of the Schottky diode at any given current is 200 to 300 millivolts less than that of the junction diode, making it an ideal low-voltage clamp.

Another major difference is the recovery characteristics, opposite page at bottom. The Schottky diode storage time is effectively zero, in contrast to typical values of 6 nsec for the gold-doped junction diode and 30 nsec for the junction diode without gold doping. In all three cases, the voltage across the diode decays with the same R-C time constant once the stored charge recombines.

The Schottky transistor is simply an npn IC transistor, produced by conventional photolithography, diffusion, and epitaxial growth techniques with an Al-Si Schottky diode in parallel with the collector-base junction. The base contact of the transistor serves as the metal contact of the diode and the collector region of the transistor serves as the n region of the diode. It's convenient to regard the npn-Schottky diode combination as a single device and to represent it by a single symbol:

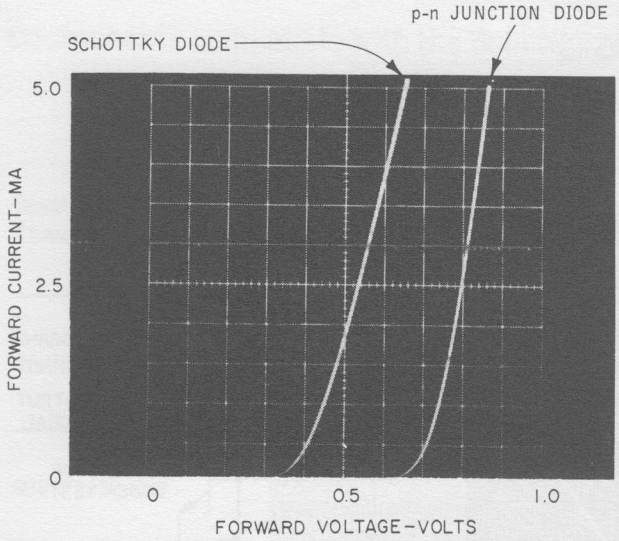


To form the Schottky transistor, the base-contact opening is extended beyond the base diffusion and over the collector region. When the aluminum metalization is deposited, it simultaneously functions as the contact to the base region and the anode of the Schottky diode. To prevent high field concentration, the metal can either be extended over the passivating oxide or terminated over a p^+ guard ring, which can be diffused into the chip at the same time as the base, as shown on page 75.

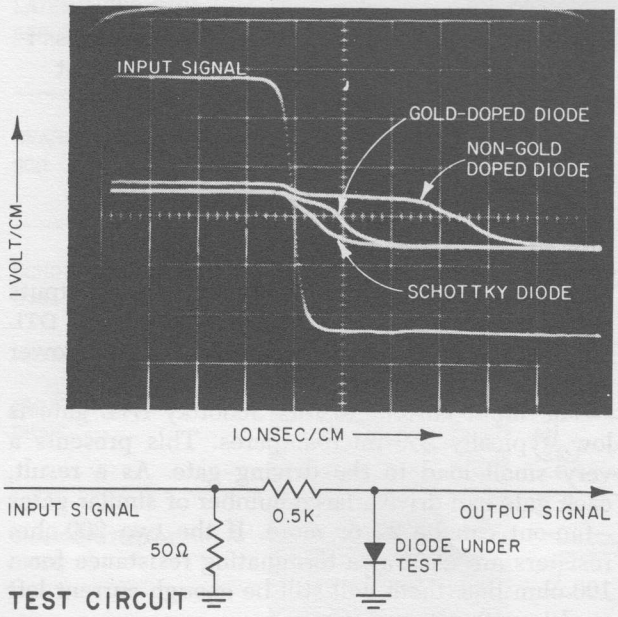
One big difference between the Schottky transistor and the conventional gold-doped npn device is in offset voltage, which is lower for the latter—typically 120 millivolts vs. 250 mv. However, the saturation voltage need not be excessive because of this large offset; by controlling both device geometry and processing, $V_{CE(sat)}$ can be kept to 0.5 volt at 20 ma collector current and 1 ma base current. And because the Schottky diode has a lower temperature coefficient than the emitter-base diode, $V_{CE(sat)}$ decreases with increasing temperature.

This behavior of the Schottky diode amounts to partial temperature compensation of the emitter-base diode and hence of $V_{CE(sat)}$. It helps to maintain a high worst-case logic 0 noise margin at high temperature when the Schottky transistor drives fan-out circuits that operate at a $2V_{BE}$ logic threshold as standard DTL and TTL IC's do.

The storage time of a Schottky transistor is effectively zero, as shown on page 78, in contrast to typically 7 nsec for a gold-doped device and 34 nsec for a non-gold-doped unit. Moreover, storage time hardly varies with temperature. At 125°C,



Forward characteristic. At 1 ma forward current, voltage drop is 0.45 volts for the Schottky diode, 0.74 volts for the p-n junction diode.



No storage. Transient characteristic shows that the Schottky diode, unlike p-n junction diodes, has essentially zero storage time.

it's still less than a nanosecond, whereas the gold-doped storage time doubles to 15 nsec at that temperature.

Aside from much faster switching speed, Schottky diodes offer the IC designer a greater range of devices to choose from. Because gold doping can't be done selectively, the designer has at his disposal only one active component: a fast switching npn transistor whose emitter-base and collector-base junctions can be used as diodes. But since the Schottky process doesn't require gold doping, the designer has seven active components to choose from. And he can mix them at will—fast- and slow-switching devices can be placed on the same chip. In both the Schottky and the gold-doped transistor, various levels of resistivity are available in the bulk material, as well as in the isolation, emitter and base diffusions for use as resistors.

Advantageous options

The Schottky diode across the base-collector junction of the npn transistor is an almost ideal active switch with less than 1 nsec storage time and high amplification. Without the Schottky diode, the device becomes a charge-storage npn transistor characterized by low saturation voltage, high inverse gain (h_{FE}), and lengthy recovery time.

Substrate pnp transistors can be diffused into the chip too; these can have h_{FE} of 10 or more and are ideal for input buffering. Lateral pnp transistors can be formed as well—with and without Schottky-clamped collectors to provide fast or slow recovery time. These devices are useful as curent sources and for voltage translation.

Then there are SCR's. Like transistors, these can be diffused into the chip in both charge-storage and Schottky-clamped versions, each of which can be optimized for different purposes. They make efficient bistable elements and give a high functional density to integrated shift registers and counters.

And, of course, there are diodes—emitter-base, charge-storage, and Schottky—each with different characteristics.

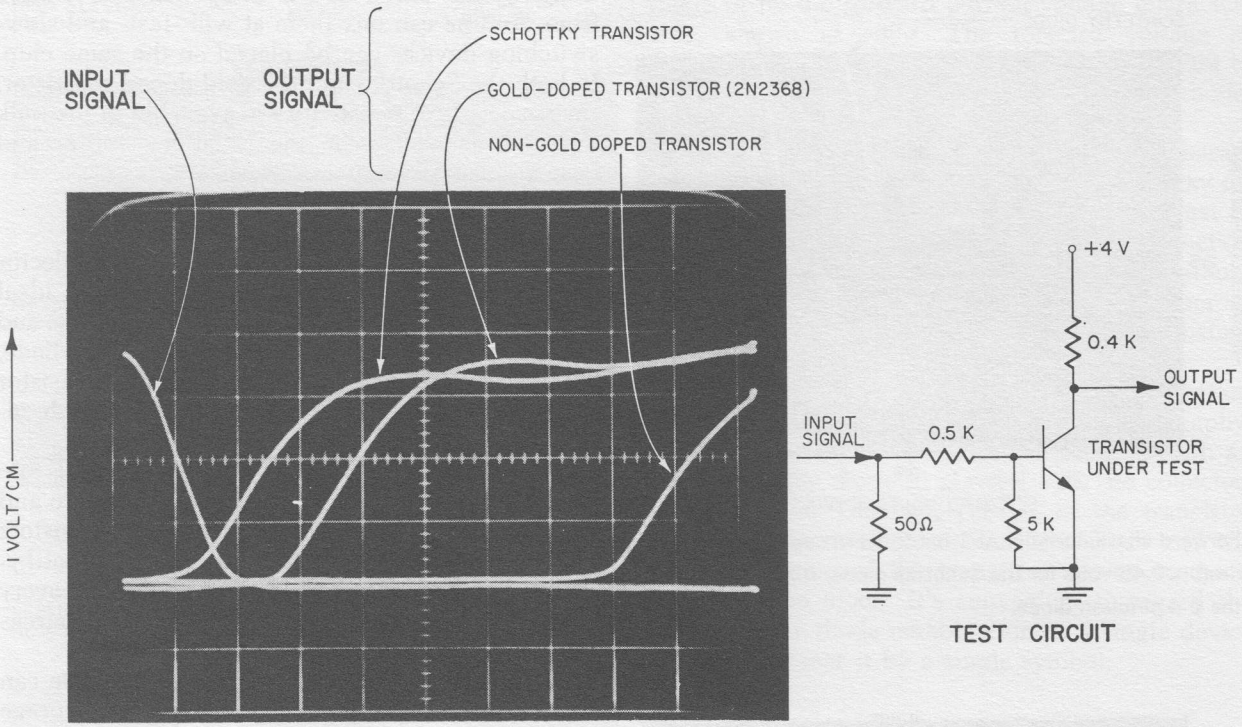
With just the Schottky diode and transistor, it's easy to upgrade old IC designs. Take DTL, for instance. If, without changing any of the resistor values, the basic DTL gate is modified with Schottky components as shown at top of page 80, the performance of the gate is improved as follows:

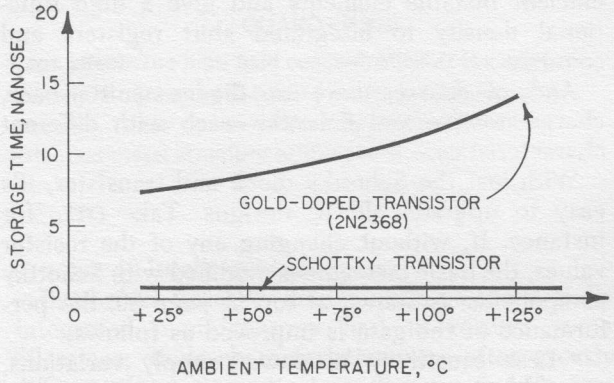
- Less sensitivity to power supply variations, since the circuit will continue to function at a lower minimum supply voltage. This is because, when all inputs are in the high state, the voltage at the base of Q_1 is typically 0.3 volts lower that it would be in the gold-doped counterpart.
- Less sensitivity to temperature variations because of the compensating effect of the Schottky diode temperature behavior.
- Faster switching; the gate turns on faster, and storage time is less than 1 nsec, remaining so throughout the operating temperature range.

In addition, modified DTL circuits can be fabricated at better yield (and lower cost to the user) because h_{FE} is higher and leakage is lower than in the gold-doped version.

The Schottky version of the TTL gate also has some important advantages over its gold-doped counterpart:

- Lower input inverse leakage current, typically less than 0.1 microampere. This is made up of the reverse-bias leakage of the emitter-base junction and the input clamp diode; there is no contribution from inverse h_{FE} since the collector base junction





Storage time. The Schottky transistor, because it doesn't store charge, responds much more rapidly to an input signal (top traces, ambient temperature 25°C). This difference becomes even more pronounced at high temperatures (bottom curves).

of the input transistor never becomes forward biased.

- Less line reflection, since the input clamp diodes—now Schottky diodes—have a lower forward-bias voltage.
- Lower power dissipation because no charge is stored (and wasted) in the transistors.
- Higher output high level, by approximately 0.3 volt.

Although the Schottky process significantly improves many of the existing circuits, its real potential lies in entirely new designs. For example, by designing from scratch with the Schottky process in mind, a DTL gate can be made just as fast as TTL. An example of such a circuit is shown on page 80, bottom left.

When the circuit is loaded with two-200-ohm resistors, as shown, the switching speed is about 5 nsec, comparable to that of the fastest TTL circuits commercially available. The advantage of DTL over TTL, given equal speeds, is that the outputs of the DTL gates can be OR-tied. Moreover, DTL doesn't create heavy current transients in the power supply during switching.

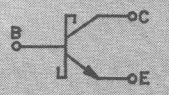
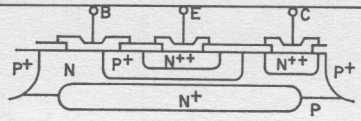
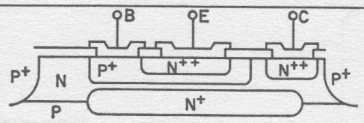
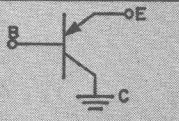
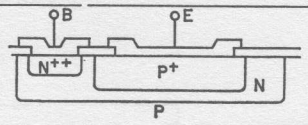
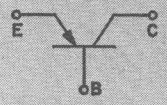
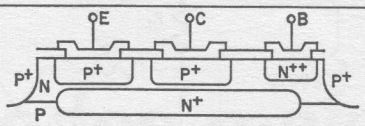
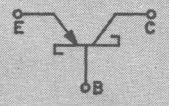
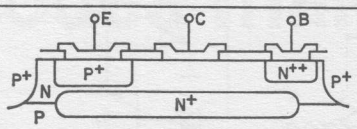
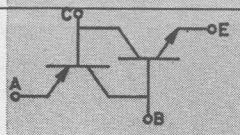
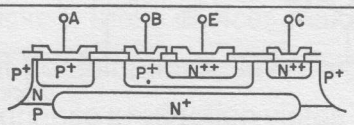
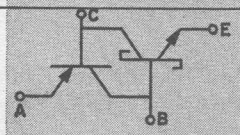
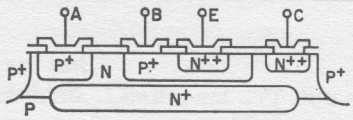
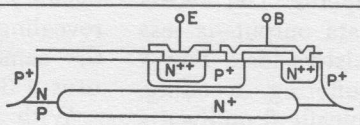
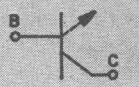
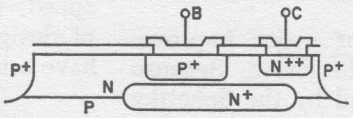
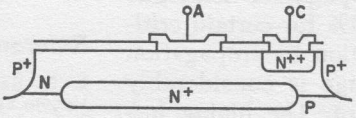
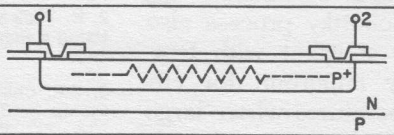
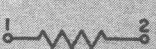
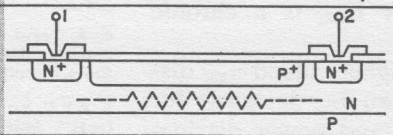
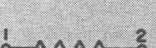
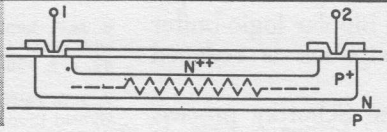
The input current to this Schottky DTL gate is low, typically 250 microamperes. This presents a very small load to the driving gate. As a result, each gate can drive a large number of similar gates —fan-out can be 25 or more. If the two 200-ohm resistors are used as a terminating resistance for a 100-ohm line, there will still be enough current left to drive 10 gates.

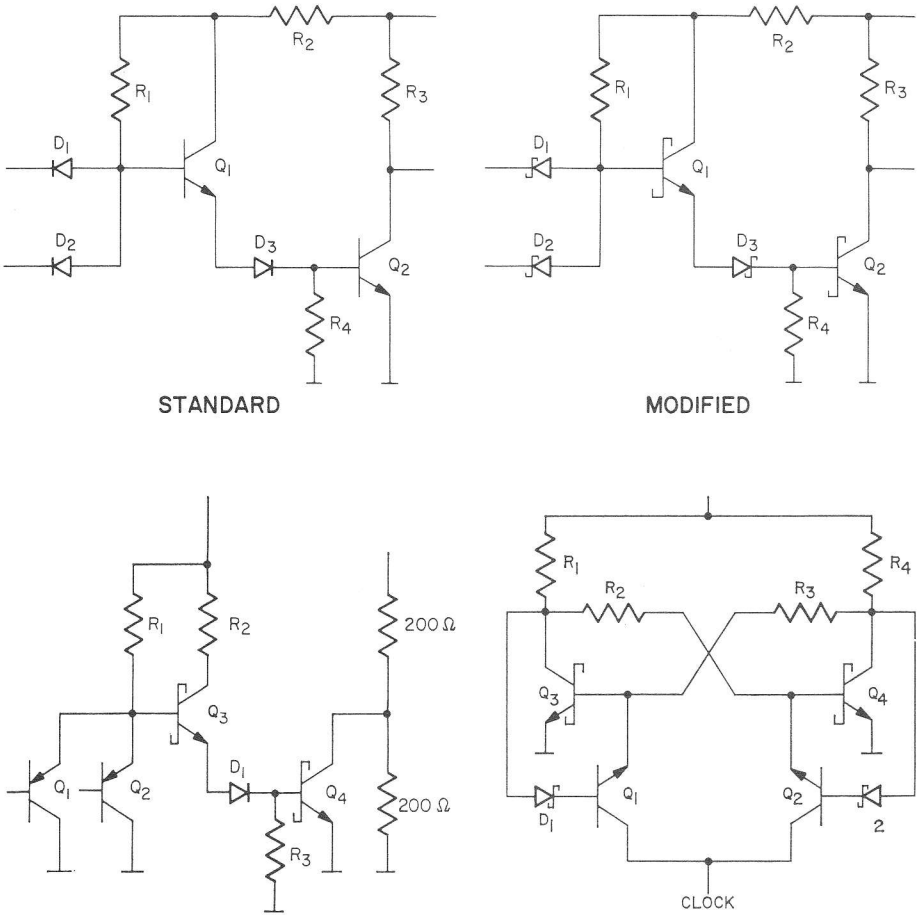
Another novel circuit is the binary divider on page 80, bottom right. It combines the best of the slow and fast worlds: the Schottky transistors that comprise the flip-flop switch at high speed, and the slow charge-storage transistors serve as temporary-data-storage elements.

Bridge work

The special advantages of these circuits, and of the Schottky process that makes them possible, are particularly applicable to complex circuits. One such IC built at Intel is a 64-bit high-speed scratch-pad memory. It's organized as 16 words by 4 bits; each of the 16 words is addressable through its own binary decoder. It has four data inputs, four address inputs, and four outputs. If it's required, the outputs can be OR-tied with the outputs of other memory

Components compatible with the Schottky process

TYPE	SYMBOL	PROFILE	PRINCIPAL CHARACTERISTICS
SCHOTTKY NPN TRANSISTOR			STORAGE TIME < 1 NSEC $V_{CE(sat)}$ = 0.2 TO 0.4 VOLT h_{FE} = 60
CHARGE-STORAGE TRANSISTOR			STORAGE TIME > 20 NSEC $V_{CE(sat)}$ < 0.1 VOLT h_{FE} INVERSE > 2
SUBSTRATE PNP			H_{FE} > 10
LATERAL PNP			H_{FE} > 2
LATERAL PNP WITH SCHOTTKY COLLECTOR			STORAGE TIME < 1 NSEC
CHARGE-STORAGE SCR			STORAGE TIME > 20 NSEC V_{ON} < 0.1 VOLT
SCHOTTKY-CLAMPED SCR			STORAGE TIME < 1 NSEC V_{ON} = 0.2 TO 0.4 VOLT
EMITTER-BASE DIODE			V_F = 0.6 TO 0.8 VOLT
CHARGE-STORAGE DIODE			STORAGE TIME > 20 NSEC
SCHOTTKY DIODE			V_F = 0.3 TO 0.5 VOLT STORAGE TIME < 1 NSEC
DIFFUSED RESISTOR			ρ_S = 100 TO 200 Ω/□
COLLECTOR-PINCH RESISTOR			ρ_S = 400 TO 1000 Ω/□
BASE-PINCH RESISTOR			ρ_S = 2 TO 10 KΩ/□



Updated. Modifying the standard DTL gate with Schottky diodes and transistors (top) affords significant performance improvement.

The new DTL. Without gold doping, many components become available to the IC designer. In the DTL gate at bottom left, input loading is reduced an order of magnitude by the substrate pnp's that replace the input diodes normally used.

Simplified. With the Schottky process, a binary counter stage (bottom right) is simple and occupies a small chip area. This is because charge-storage transistors (Q_1 and Q_2, which are incompatible with the gold-doped process, can be used to store information.

integrated circuit chips.

The input load is equal to one unit TTL load, and the output can sink 20 milliamperes. The access delay—from address input to data output—is less than 50 nsec under a 20 ma resistive load. Power dissipation, including address buffering, decoding, sensing, and control logic, is typically 6 milliwatts per bit.

These specifications represent major improvements over gold-doped IC performance. Because storage time has been eliminated by the Schottky process, the input-to-output propagation delay has been reduced by as much as 40% for certain critical delay paths. And the variation in propagation delay due to temperature change is considerably less than in a gold-doped circuit. The higher h_{FE} values that result from the Schottky process also help keep propagation delay constant with temperature. This is particularly important for circuits that operate at low temperatures where large increase in delay, due to low h_{FE}, is a chronic problem in gold-doped IC's.

Another advantage of this higher-valued h_{FE} distribution is that transistors can be designed for higher forced-beta conditions, and power dissipation is therefore lower. For the bipolar logic-buffer chip, for example, power dissipation is reduced by about 30%.

Most significant, perhaps, the Schottky process has resulted in higher functional density and smaller chips. A comparison of the Intel 64-bit memory with an equivalent gold-doped circuit is revealing: Although the gold-doped IC is made with the same mask tolerances, the Schottky version uses a 30% smaller chip.

With all that they have going for them—high speed, greater functional density, and flexibility of design—Schottky-diode IC's certainly appear to have a bright future.

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